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Soft Spin Wave Near ν=1: Evidence for a Magnetic Instability in Skyrmion Systems.

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The ground state of the two dimensional electron gas near ν=1 is investigated by inelastic light scattering measurements carried down to very low temperatures. Away from ν=1, the ferromagnetic spin wave collapses and a new low-energy spin wave emerges below the Zeeman gap. The emergent spin wave shows soft behavior as its energy increases with temperature and reaches the Zeeman energy for temperatures above 2 K. The observed softening indicates an instability of the two dimensional electron gas towards a magnetic order that breaks spin rotational symmetry. We discuss our findings in light of the possible existence of a Skyrme crystal.

In condensed matter physics, the competition between distinct correlated electron ground states follows from a delicate interplay between dimensionality, strength of Coulomb interactions, and disorder. Correlated states may possess long range spin and/or charge order that breaks a symmetry that, in turn, has profound consequences on the nature of the low-energy excitation spectrum [1, 2]. One well-known example of the relationship between broken-symmetry and elementary excitations is the isotropic ferromagnet. The broken rotational spin symmetry leads to appearance of gapless spin wave excitations, Goldstone modes, that are fluctuations of the spin density around the magnetization direction.

The ground state of the two-dimensional (2D) electron gas at Landau level filling factor ν=1 is a special kind of itinerant ferromagnet, the quantum Hall ferromagnet, where all electrons occupy the lowest orbital Landau level and their spins are aligned along the external magnetic field. The quantum Hall ferromagnet supports collective excitations similar to ferromagnetic spin-waves with a gap given by the bare Zeeman energy E_z [3, 4]. The quantum Hall ferromagnet also has spin texture excitations built from Skyrmions [5, 6], a concept used to describe the emergence of nuclear particles in the context of field theories of nuclear matter [7]. Skyrmions are topological objects which smoothly distort the ferromagnetic order in a vortex-like configuration. Each individual Skyrmion involves several flipped spins and is therefore not favored by the Zeeman energy. On the other hand because the exchange energy is large in quantum Hall systems, and it prefers locally aligned spins, Skyrmions are cheaper than single spin-flips for sufficiently low E_z. The relevance of Skyrmions has been demonstrated by a wide range of experiments probing the spin polarization of the 2DES [8–11].

Near ν=1 the interaction between Skyrmions may lock orientations of spin in the XY plane to favor the formation of a Skyrme crystal of electron spin orientation that breaks spin rotational symmetry about the magnetic field axis [12]. As a consequence of the additional symmetry breaking, the 2D electron system supports spin waves which, contrary to the ferromagnetic spin wave, remain gapless in the presence of the magnetic field [13–15]. Both a jump in the specific heat and the very short T_1 observed away from ν=1 were interpreted as indirect consequences of the enhanced coupling between the nuclear spins and the electron system due to the gapless spin waves (Goldstone mode) of the Skyrme crystal [16–18].

While most studies of Skyrmions have focused solely on their impact on electron spin polarization, no experiment has explored up to now the possibility of exploring Skyrmion interactions and the magnetic ground state of the 2DES near ν=1 by probing long-wavelength spin wave excitations. Measurements of spin wave excitation are especially valuable since they are expected to reflect the presence of a broken symmetry state arising from XY spin ordering [14].

Here we report the direct observations of spin-wave excitations well below the Zeeman energy. These spin waves emerge near the quantum Hall state at ν=1. The excitations are measured directly by inelastic light scattering in experiments that search for fingerprints of a broken symmetry ground state by looking at the evolution of spin wave excitation spectra at low temperatures.

Very close to ν=1, the spectrum is dominated by the ferromagnetic spin wave at energy near E_z. Tuning the filling factor slightly away from ν=1 at low temperatures T<2 K alters dramatically the spin excitation spectrum. The ferromagnetic spin wave is strongly suppressed on both sides of ν=1 signaling the rapid collapse of the quantum Hall ferromagnetic order. Simultaneously, a new low energy spin excitation emerges well below the Zeeman energy. Strikingly the new spin wave displays soft mode behavior with temperature and a mode at E_z is recovered for T>2 K.

Our findings indicate an instability towards a ground state with spin orientational order at very low temperature that is linked to Skyrmion interactions. The spin order is consistent with the Skyrme crystal phase where the Skyrmions localize on a square lattice and the XY spins of neighbouring Skyrmions are antiferromagnetically aligned [12].

Further away from ν=1, the spin wave anomalies, seen as spectral weight below the Zeeman energy, gradually disappear and at ν=2/3 the spin excitation spectrum is gapped as a conventional quantum Hall ferromagnetic spin wave. The evolution of the low energy spin excitation spectrum away from ν=1 suggests a transition from a Skyrmion dominated regime close to ν=1 and a spin polarized regime at filling factors close to fractional quantum Hall liquids.

The inelastic light scattering measurements were performed on a high quality GaAs single quantum well of width 330 $\mathring{A}$. Its density is n=5.5x10^{10} cm^{-2} and its low temperature mobility μ=7.2x10^6 cm^2/V s. The magnetic field perpendicular to the sample is B=B$_T$cosθ as shown in the top inset of Fig. 1. The results reported here have been obtained with θ=50±2°. The combination of tilt angle and electron density gives a ratio of Zeeman to Coulomb energy, E$_z$/E$_c$=0.0134, where E$_c$ = $e^2/\varepsilon l_o$, $l_o = (\hbar c/eB)^{1/2}$ is the magnetic length and ϵ is the dielectric constant. This ratio lies in the regime where Skyrmions excitations are cheaper than single spin-flips [19, 20]. The sample was mounted on the cold finger of a ^{3}He/^{4}He dilution refrigerator that is inserted in the cold bore of a superconducting magnet. The refrigerator is equipped with windows for optical access. Cold finger temperatures can reach as low as T=40 mK.

Resonant inelastic light scattering spectra were obtained by tuning the photon energy of a Ti-Sapphire laser close to the fundamental optical gap of GaAs. The back scattering geometry was used where the incident laser beam makes an angle θ with the normal of the sample surface (see the top inset of Fig.1). The wave vector transferred from the photon to the electron system is $q = k_L - k_S = (2\omega_L/c) sin\theta$, where $k_{L(S)}$ is the in-plane component of the wave vector of the incident (scattered) photon. q=1.2x10^5 cm^{-1} for $\theta = 50°$. The power density was kept around 10^{-5} W/cm^2 to prevent heating of the electron gas. The scattered signal was dispersed by a triple grating spectrometer working in additive mode and analyzed by a CCD camera with 26 μm wide pixels. At a slit width of 30 μm, the combined resolution of the system is about 0.02 meV.

Figure 1 displays the filling factor dependence of the spectrum in the filling factor range 0.75< ν <1.32 at T∼40 mK. All the features appear predominantly in the depolarized configuration (VH) which, according to light scattering selection rules, indicates their spin origin [21]. At ν=1 the spectrum consists of a single sharp (FWHM∼30 μeV) peak which is identified as the ferromagnetic spin wave (SW) at the wave vector q. Its energy is blue-shifted from E$_z$ due to the combined effects of the finite wave vector transfer q and the large spin-stiffness of the ν=1 quantum Hall ferromagnet [22].

Slight departures from ν=1 have major impact on the the spin wave spectra for *both* ν <1 and ν >1. Surprisingly, the ferromagnetic spin wave intensity is strongly suppressed leaving a weak and broad peak at higher ener-

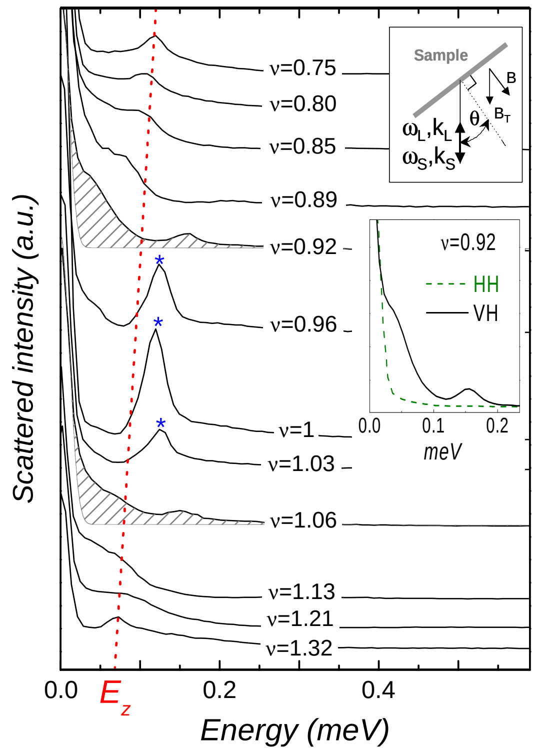

FIG. 1: (color online) Filling factor dependence of inelastic light scattering spectra for 0.75< ν <1.32 at T∼40 mK. The blue star marks the ferromagnetic spin wave close to ν=1. The red dotted line displays the approximate evolution of the bare Zeeman energy with magnetic field assuming E$_z$=gμ_BB$_T$ with g=-0.44. The shaded area in the ν=0.92 and 1.06 highlights the spectral weight emerging below E$_z$. The insets show the scattering geometry and the polarization dependence of the spectrum at ν=0.92. HH and VH indicate configurations in which the incident and scattered photons are parallel and perpendicular respectively.

gies (at ν=0.92 and ν=1.06 for example). At low energy, the suppression of the ferromagnetic spin wave is accompanied by the emergence of a strong spectral weight *below* E$_z$, with a spectral response that extends essentially to zero energy. The low-lying spectral weight appears particularly large for the spectra at ν=0.92 and 1.06 but it is already present, albeit weaker, for ν=0.96 and ν=1.03. Further away from ν=1, a well-defined peak at E$_z$ is recovered (see spectra at ν=0.75 and 1.32 in Fig.1).

The collapse of the ferromagnetic spin wave suggests a rapid spin depolarization away from ν=1 due to the collapse of the spin order of the ferromagnetic quantum Hall state. The simultaneous appearance of a low-energy spectral weight on both sides of ν=1 indicates the presence of spin excitations well below the Zeeman gap. The occurrence of electron spin excitations at very low energy explains the very short nuclear spin relaxation times T$_1$ observed in NMR experiments in the same filling factor range [10, 17, 18, 23–25].

Slightly away from ν=1, the spin excitation spectrum

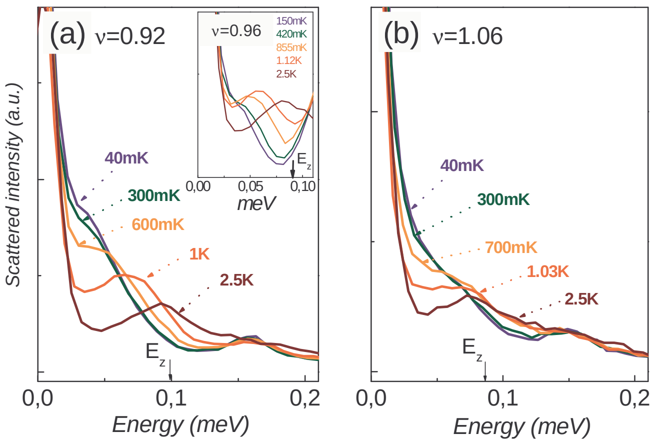

FIG. 2: (color online) Temperature dependence of the light scattering spectra at (a) ν=0.92 (B$_T$=4.0 T) and (b) 1.06 (B$_T$=3.5 T). The Zeeman energy, E$_z$, is marked by an arrow for both filling factors. The inset in (a) shows the temperature dependence of the low energy spectrum at ν=0.96 (B$_T$=3.85 T).

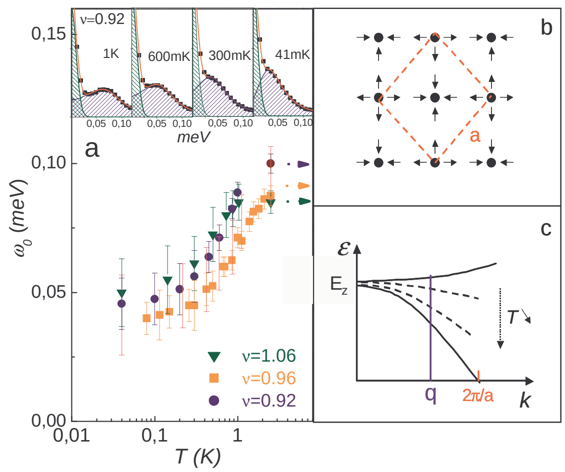

FIG. 3: (color online) (a) Temperature dependence of the spin wave energy for ν=1.06, ν=0.96 and ν=0.92. The Zeeman energies for each filling factor are marked by arrows. The inset shows fits of the spectra at ν = 0.92 for 4 different temperatures. The stray light and damped oscillator mode contributions (see text) are highlighted. (b) A schematic representation of the XY component of the spin for a square Skyrme crystal with lattice parameter a showing antiferromagnetic (AF) ordering of the XY spin components of neighbouring Skyrmions [12]. (c) Evolution of the spin wave dispersion as function of temperature where k$_{sk}$=2π/a.

displays the striking temperature evolution seen in Fig. 2 at ν=0.92 and 1.06 (see also ν=0.96 in the inset). For both filling factors the spin excitation spectrum at 2.5 K is dominated by a relatively broad peak centered close to the Zeeman energy. Upon cooling however, the peak continuously evolves towards lower energy and below approximately 0.6 K most of the spectral weight has already shifted well below E$_z$ and close the central peak (stray light) centered at zero energy. We emphasize that this temperature dependence is only observed in a rather narrow filling factor range $|\nu - 1| \sim [0.04; 0.10]$.

Focusing on the low energy part of the spectra (i.e. $\omega \leq$E$_z$), we have modelled it by a damped oscillator mode response [26]:

$$I(T,\omega) \sim (1+n(\omega,T))\frac{\omega\gamma(T)}{(\omega^2-\omega_0^2(T))^2+\omega^2\gamma^2(T)} \quad (1)$$

where $I(T,\omega)$ is the scattered intensity, $\omega_0(T)$ the mode energy, $\gamma(T)$ the damping and n(ω,T) is the Bose-Einstein factor. The stray light central peak was fitted using a gaussian profile centered at ω=0 (see Fig.3). The low-energy spectra are well reproduced at all temperatures using this simple analysis. The spin wave remains overdamped at all temperatures and its energy continuously evolves towards lower energies upon cooling for ν=1.06, ν=0.96 and ν=0.92 as shown in Fig. 3(a).

The striking softening of the spin wave that occurs at temperatures below 2.5 K seen in Figs. 2 and 3(a) shows a trend towards a magnetic instability for filling factors in the range $|\nu - 1| \sim [0.04; 0.10]$. From a gapped spectrum consistent with ferromagnetic spin order along the z direction (magnetic field direction) only, the system gradually evolves upon cooling towards a spectrum with essentially gapless spin excitations indicating a state with additional in-plane XY spin order [13]. In this scenario the softening of the spin wave below the Zeeman energy is connected to a *spontaneous breaking of spin rotational symmetry* that is consistent with the antiferromagnetic (AF) alignment of XY spin components like the one predicted for a Skyrme crystal phase and shown in Fig. 3(b) [12, 14].

The softening of the spin wave is expected to occur around the reciprocal lattice wave-vector k_{sk} of the new XY AF magnetic lattice sketched in Fig. 3(c). A proposed temperature evolution of the spin wave dispersion is depicted in Fig. 3(d): starting from a conventionnal ferromagnetic quadratic dispersion which is gapped at E$_z$ the dispersion shows a developping anomaly at the reciprocal magnetic lattice wave-vector, k_{sk} as the temperature is decreased. We emphasize here that the sensitivity of our experiment to the magnetic instability is crucially linked to the fact that we are probing the spin wave excitation spectrum at a wave vector q that is in the range of the expected lattice wave vector of the square Skyrme crystal in the filling factor region of interest [29].

While our data are strong evidences for a ground state with broken spin rotational symmetry that is consistent with a Skyrme crystal picture, we cannot rule out however a correlated Skyrme liquid phase with long range spin orientationnal order only and no long range translational order. Both states, liquid ans crystal, are expected to have a similar spin excitation spectrum [14].

Figure 4 shows the evolution of the spin excitation

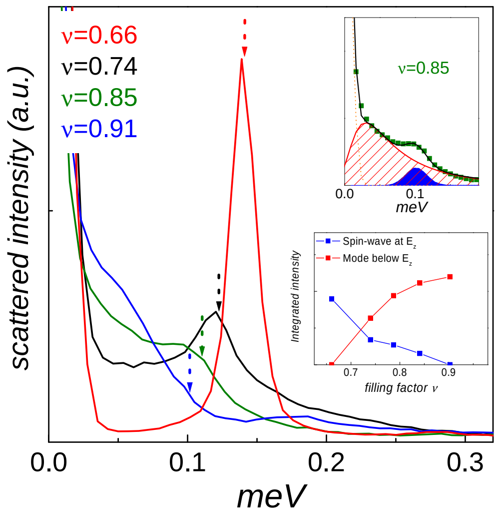

FIG. 4: (color online) Filling factor dependence of the low energy spectrum at T=40 mK. The bare Zeeman energy is marked by an arrow for each filling factors. For $\nu < 0.85$ the additional spin wave at E_z was modelled by a gaussian profile. The inset shows an example of fit for ν=0.85 with the spin wave below E_z in red and the ferromagnetic spin wave contribution in blue. Also shown as inset is the filling factor dependence of the spectral weights of the two contributions.

spectrum at 40 mK for $\nu < 0.9$. When movig further away from ν=1, the new low energy the spin wave broadens significantly and the spectral weight below E_z decreases drastically. Simultaneously a well-defined spin wave, centered at E_z, develops and the spin excitation spectra become almost temperature independent below 1 K for $\nu < 0.85$ (not shown). When ν=2/3 is reached the spectrum is gapped with vanishing spectral weight below E_z. It displays a well-defined ferromagnetic spin wave similar to ν=1, suggesting a spin polarized quantum Hall fluid at this filling factor.

The filling factor dependence of the spectral weight of both the spin wave below E_z and the ferromagnetic spin wave at E_z shown in the bottom inset of Fig. 4 suggests a crossover between spin polarized quantum Hall fluids with gapped spin-flip excitations and Skyrmions ground states in the filling factor range $2/3 < \nu < 1$ [27, 28]. The behavior can be qualitatively understood as follows: as the density of Skyrmions increases upon decreasing filling factor, their size decreases until they become equivalent to single spin-flips and conventional fractionnal quantum Hall fluids emerge.

To conclude, we have reported direct measurement of the low energy spin excitation spectrum around ν=1. Slightly away from ν=1, a low-lying soft spin wave is observed, indicating a ground state with broken spin rotational symmetry that arises from magnetic interaction between neighbouring Skyrmions.

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